

Muon Cooling R&D

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Abstract

International efforts are under way to design and test a muon ionization cooling channel. The present R&D program is described, and future plans outlined.

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1 Introduction

Recently there has been widespread interest in developing a very intense muon source capable of producing a millimole of muons per year. If the muons are then accelerated to high energies, they could be used in a Neutrino Factory [1], and perhaps eventually a Muon Collider [2].

The muons are to be produced using an intense proton source to make low energy charged pions, which are confined within a large acceptance decay channel. The daughter muons produced from π^\pm decays will occupy a large phase-space volume. Before the muons can be accelerated the transverse phase-space they occupy must be reduced so that the muon beam fits within the acceptance of an accelerator. This means we must “cool” the transverse phase-space by at least a factor of a few in each transverse plane. This must be done fast, before the muons decay. Stochastic- and electron-cooling are too slow. It is proposed to use a new cooling technique, namely “ionization cooling” [3].

In an ionization cooling channel the muons pass through an absorber in which they lose transverse- and longitudinal-momentum by dE/dx losses. The longitudinal momentum is then replaced using an RF cavity, and the process is repeated many times, removing the transverse muon momenta. This cooling process will compete with transverse heating due to Coulomb scattering. To

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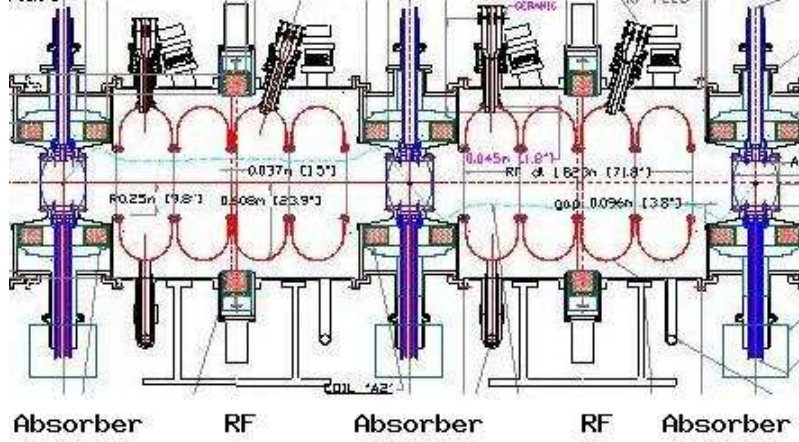


Fig. 1. SFOFO cooling channel design. A 5.5 m long section is shown, consisting of two 200 MHz four-cell cavities interleaved with three liquid hydrogen absorbers.

minimize the effects of scattering we chose low- Z absorbers placed in the cooling channel lattice at positions of low- β_{\perp} so that the typical radial focusing angle is large. If the focusing angle is much larger than the average scattering angle then scattering will not have much impact on the cooling process.

2 Cooling Channel Design in the US

In the last 18 months there have been two Neutrino Factory “Feasibility” Studies [4] in the US which have involved end-to-end design studies, together with detailed simulations for each piece of the Neutrino Factory complex. The studies have used two simulation tools developed by the Neutrino Factory and Muon Collider Collaboration: (i) A specially developed tracking code ICOOL, and (ii) A GEANT based program with accelerator components (e.g. RF cavities) implemented. Out of these design and simulation studies, two promising cooling channel designs have emerged:

- (i) The “SFOFO” lattice in which the absorbers are located at low- β_{\perp} locations within high-field solenoids. The field rapidly decreases from a maximum to zero at the absorber center, and then increases to a maximum again with the axial field direction reversed. Figure 1 shows the design for a 5.5 m long section of the ~ 100 m long cooling channel. The section shown has 30 cm long absorbers with a radius of 15 cm, within a 3.5 T axial field. Towards the end of the cooling channel the maximum field is higher (5 T) and the lattice period shorter (3.3 m). The RF cavities operate at 200 MHz and provide a peak gradient of 17 MV/m. Detailed simulations predict that the SFOFO channel increases the number of muons within the accelerator acceptance by a factor of 3-5 (depending on whether a large- or very-large acceptance accelerator is used).

(ii) The “DFLIP” lattice in which the solenoid field remains constant over large sections of the channel, reversing direction only twice. In the early part of the channel the muons lose mechanical angular momentum until they are propagating parallel to the axis. After the first field flip the muons have, once again, mechanical angular momentum, and hence move along helical trajectories with Lamour centers along the solenoid axis. Further cooling removes the mechanical angular momentum, shrinking the beam size in the transverse directions. The field in the early part of the channel is 3 T, increasing to 7 T for the last part. Detailed simulations show the performances of the DFLIP and SFOFO channels are comparable.

Earlier less detailed studies [2] have shown that a much larger cooling factor will be required for a muon collider. This will require an extended cooling channel, using higher frequency (e.g. 805 MHz) cavities and higher field solenoids.

3 MUCOOL R&D

The mission of the MUCOOL collaboration is to design, prototype, and bench-test all cooling channel components, and eventually beam-test a cooling section. The main component issues are (i) can sufficiently high gradient RF cavities be built and operated in the appropriate magnetic field and radiation environment, (ii) can liquid hydrogen absorbers with thin enough windows be built so that the dE/dx heating can be safely removed, and (iii) can the lattice solenoids be built to tolerance and be affordable? The MUCOOL collaboration has embarked on a design-, prototyping-, and testing-program for all these components. This is expected to proceed over the next 3 years.

3.1 805 MHz RF Tests

Early design work for a Muon Collider showed that the cooling channel requires 805 MHz cavities operating in a 5T solenoid, and providing a peak gradient of ~ 30 MV/m. This deep potential well is needed to keep the muons bunched as they propagate down the channel. This requirement led to two cavity concepts: (a) an open cell design, and (b) a design in which the penetrating nature of the muons is exploited by closing the RF aperture with a thin conducting Be window (at fixed peak power this doubles the gradient on axis).

The MUCOOL collaboration has pursued an aggressive 805 MHz cavity development program, which is now advanced. The main results to date are: (i) A 12 MW high power test facility has been built and operated at Fermilab (Lab G). The Lab G facility enables 805 MHz cavities to be tested within a 5T



Fig. 2. High power 805 MHz cavity test in the MUCOOL Lab G test area, Fermilab.

solenoid. (ii) An open cell cavity suitable for a muon cooling channel has been designed, an aluminum model built and measured, and a prototype copper cavity built, tuned, and successfully tested at full power in the Lab G facility. (iii) A Be foil cavity has been designed at LBNL, a low power test cavity built and measured, and foil deflection studies made to ensure the cavity does not detune when the foil is subject to RF heating. A high power copper cavity with Be-foil windows is under construction at LBNL and the University of Mississippi, and will be tested at Lab G when ready.

3.2 200 MHz Cavity Development

The cooling channel designs developed for the US Neutrino Factory studies require 200 MHz RF cavities providing a gradient on axis of ~ 17 MV/m. Preliminary cavity designs have been made. There are two concepts, both of which close the cavity aperture. The options are to use (a) a thin Be foil, exploiting the work done for the 805 MHz cavity, or (b) use a grid of hollow conducting tubes. Preliminary mechanical tests for both the grid and foil concepts are planned, and should proceed during the next few months. A 200 MHz prototype cavity will then be constructed, and should be ready for high power tests in about 2 years.

Table 1
 LH_2 absorber parameters in Neutrino Factory design study II.

Absorbers	Length (cm)	Radius (cm)	Number Needed	Heat (kW) Deposited	Window Thick- ness (μm)	Max. Pres- sure (atm)
Early	35	18	16	~ 0.3	360	1.2
Late	21	11	36	~ 0.1	220	1.2

3.3 Absorber Development

The cooling channel liquid hydrogen absorbers must have very thin windows to minimize multiple scattering, and must tolerate heating of $\text{O}(100 \text{ W})$ from the ionization energy deposited by the traversing muons. Absorber parameters for the Neutrino Factory study II cooling channel design are listed in Table 1.

To adequately remove the heat from the absorbers requires transverse mixing of the liquid hydrogen. There are two design concepts that are being pursued: (i) Forced flow design. The LH_2 is injected into the absorber volume through nozzles, and cooled using an external loop and heat exchanger. (ii) Convection design. Convection is driven by a heater at the bottom of the absorber volume, and heat removed by a heat exchanger on the outer surface of the absorber. A forced flow absorber prototype has been designed at the Illinois Institute of Technology (IIT) and is under construction. A convection prototype has been designed by IIT, KEK, and the University of Osaka, and is under construction in Japan. Both absorbers will be tested at Fermilab when complete.

A first prototype 15 cm radius aluminum absorber window has been made at the University of Mississippi on a CNC milling machine and lathe. The window has a central thickness of $130 \mu\text{m}$. The window thickness and profile were measured at FNAL and found to be within 5% of the nominal envelope. This verifies the manufacturing procedure. The window has been tested under pressure in a setup at Northern Illinois University in which it was mounted on a backplate and water injected between window and plate. Strain gauge and photogrammetric measurements were made as a function of pressure, and the results compared with FEA predictions. Onset of inelastic deformation was predicted at 29 psig, a pinhole leak appeared at 31 psig, and rupture occurred at 44 psig. The windows required for a cooling channel absorber can be about twice as thick as the first prototype window. The results to date are therefore encouraging. Further window studies and tests are proceeding.

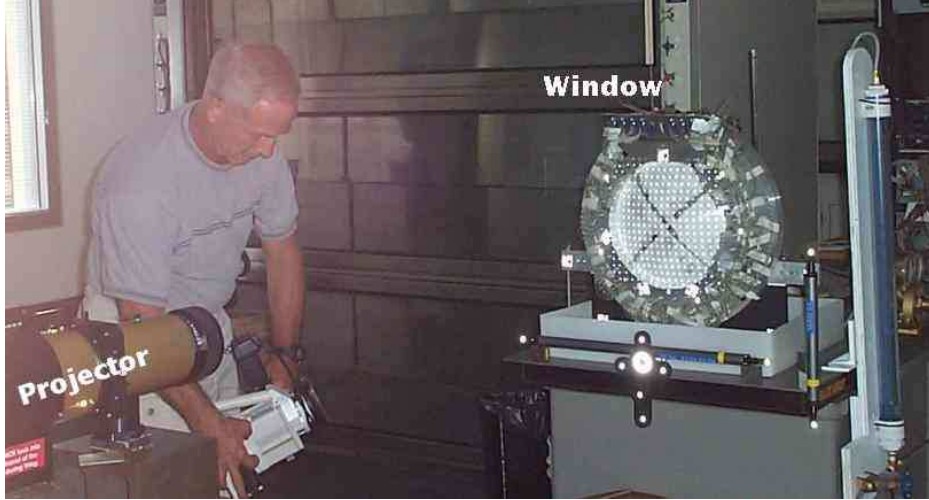


Fig. 3. Absorber window test, showing an array of dots projected onto the window for photogrammetric measurements of its shape as it deforms under pressure.

4 European R&D Program

The CERN cooling channel design is similar in concept to the US design, but is based on 44 MHz and 88 MHz cavities rather than 200 MHz cavities. To minimize the radii of the solenoids used to confine the muons within the channel, the cavities have been designed to wrap around the solenoids. A full engineering design of this concept will be required to understand its feasibility. The initial transverse cooling is performed using 44 MHz cavities with four 1 m long RF cells between each 24 cm long LH_2 absorber. The beam is then accelerated from 200 MeV to 300 MeV, and the cooling is continued using 88 MHz cavities with eight 0.5 m long cells between each 40 cm long LH_2 absorber. The channel parameters are summarized in Table 2. Simulations of the channel performance with detailed field-maps have not yet been made. However, simulations using simpler field maps yield promising results: the effect of the channel is to increase the number of muons within the acceptance of the subsequent accelerating system by a factor of about 20. Whether this increased yield is significantly degraded when full simulations are performed remains to be seen. In the meantime, a prototype 88 MHz cavity is being prepared at CERN for high power tests within the coming year.

5 Cooling Experiments

A sequence of muon cooling-related experiments is being planned. The first, the MUSCAT experiment [5], is already under way at TRIUMF. The second, the MUCOOL Component Test Experiment, is under construction at

Table 2
CERN cooling channel design parameters.

	Channel 1	Channel 2
Length	46 m	112 m
Diameter	60 cm	30 cm
Sol. Field	2.0 T	2.6 T
RF Freq.	44 MHz	88 MHz
RF Gradient	2 MV/m	4 MV/m
Beam Energy	200 MeV	300 MeV

the Fermilab LINAC. The third, an International Cooling Experiment [6], is in the planning stage. The fourth, an eventual String Test Experiment, will be planned in the future.

5.1 MUSCAT

The goal of the MUSCAT experiment at TRIUMF is the precise measurement of low energy (130, 150, and 180 MeV/c) muon scattering in a variety of materials that might be found with a cooling channel. In a second phase, the experiment will also measure straggling. Scattering measurements for Li, Be, C, Al, CH₂, and Fe have already been made. Preliminary results seem to be in good agreement with expectations. Further analysis is in progress. Measurements with LH₂ are expected in the future.

5.2 The MUCOOL Component Test Experiment

A MUCOOL test area located at the end of the Fermilab 400 MeV LINAC was proposed in the Fall of 2000, and is currently under construction. The project is being pursued in two phases. In Phase 1 a LH₂ absorber test facility is being built, which will enable the first prototype absorbers to be filled. In Phase 2 the test area will be enlarged, a LINAC beam will be brought to the absorber area, and the 5T solenoid will be moved from Lab G so that the absorber can be tested in a magnet whilst exposed to a proton beam. The beam intensity and spot size will be designed to mimic the total ionization energy deposition and profile that corresponds to the passage of $10^{12} - 10^{13}$ muons propagating through a cooling channel. In addition, 200 MHz RF power will be piped to the test area from a nearby test-stand, enabling high-power tests to be made of a prototype 200 MHz cooling channel cavity exposed to the proton beam.

5.3 *The International Cooling Experiment*

A Europe-Japan-US International Cooling Experiment is currently being planned. The goals are to (i) place a cooling channel section (capable of achieving the performance required for a Neutrino Factory) in a muon beam, and (ii) demonstrate our ability to precisely simulate the passage of muons confined within a periodic lattice as they pass through LH₂ absorbers and high-gradient RF cavities. In the envisioned experiment muons are tracked one at a time at the input and output of the cooling section, and the precise response of the muons to the cooling section is determined. The main challenge to the design of this type of experiment arises from the prolific x-ray environment created by the RF cavities. This is currently under study at Lab G and elsewhere. If it is found that single particle detectors can function in this hostile environment, then we can anticipate a proposal being submitted sometime in 2002.

6 Summary

Detailed simulations show that a muon ionization cooling channel for a Neutrino Factory is feasible provided RF cavities and LH₂ absorbers can be built to meet aggressive performance specifications. A component R&D program is underway to prototype and test cooling channel components. An International Cooling Experiment proposal is being prepared. If there is adequate support for this R&D, in a few years we should be in a position to choose the best cooling channel design, based on components with verified performance.

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